

# **A Methodology to Optimize Hierarchical Clock Skew by Clock Delay Compensation**

## **Background of the Invention**

### **Field of the Invention**

5 [0001] The present invention relates generally to methods and apparatus for the design, partition, and placement of microelectronic integrated circuits. More specifically, the present invention is related methods and apparatus for the design and construction of a hierarchical clock distribution system within microelectronic integrated circuits. Even more particularly the present invention  
10 relates to methods and apparatus for compensating for clock skew within the clock distribution system between functional circuit blocks of the integrated circuits.

### **Description of Related Art**

[0002] Electronic Design Automation (EDA) tools and methods facilitate the  
15 design, partition, and placement of microelectronic integrated circuits on a semiconductor substrate. Generally transistors are formed into primitive circuits that perform digital logic functions such as AND, OR, NAND, NOR, etc. The primitive circuits are then organized into macro circuits such as multiplexers, adders, multipliers, decoders, etc., which in turn are organized as functional  
20 blocks. In a hierarchical design, the functions of the integrated circuit design are allocated space on the semiconductor substrate. Each of the individual functions

is then partitioned into the various macro circuits which are often predesigned and placed in a library of the EDA system. When the individual functional designs are completed, the global design of the whole integrated circuit is then completed to interconnect the individual functional blocks.

5 [0003] In a synchronous logic design, a common timing signal or clock is employed to insure that the circuitry functions correctly. The clock is distributed to each of the registers or latches within the functions and ideally arrives at each of the latches simultaneously during operation. In reality this is not true. There are differences in the distribution of the clock which causes variation in the arrival  
10 of the clock at each of the registers or latches. This variation is referred commonly as "clock skew".

[0004] Refer now to Fig. 1 for a discussion of the structure of a clock distribution system for an integrated circuit of the prior art and the contributing factors to the clock skew. The primitive logic circuits are configured to form a combinational  
15 logic function **115**. The registers **110** and **120** provide the memory elements for groups of the sequential logic functions **100**. The sequential logic functions **100** are partitioned and organized to form the individual macro-function logic blocks. The macro-function logic blocks are arranged and placed physically on the semiconductor substrate.

20 [0005] A clock generator **125** provides the clock timing signal used to provide the synchronization of the data being transferred to and transferred from the registers. The clock timing signal is transferred through a clock distribution

system or clock tree from the clock generator **125** to the registers **110**. The clock distribution system or clock tree is a series of buffer circuits placed in an ever widening network or subtrees **135**, **140**, and **145**. Each buffer is generally a driver circuit constructed to provide an increment of delay to the clock timing signal and sufficient drive for the number of buffers in the next layer of buffers.

[0006] In the example of the clock distribution system, as shown, the clock timing signal is received from the clock signal generator **125** by the buffer **130**. The buffer **130** forms a first layer of the clock distribution system or clock tree. The output of the buffer **130** is connected to the second layer of buffers **132**. Each of the buffers of the second layer of buffers **132** is in turn connected to a group of buffers of the third layer of buffers **134a**, ..., **134z**. The first, second, and third layers of buffers form the global or top level of the clock distribution system and provide the interconnections to distribute the clock timing signal to the macro-function logic blocks. The global or top layer clock distribution system may provide a balanced common subtree **135**

[0007] The clock distribution system is further distributed through the clock subtrees **140** and **145** to the sequential logic functions **100**. In the example as shown the output of the buffer **134b** is connected to the buffers **142** and **146**. The outputs of the buffers **142** and **146** are connected respectively to a group of buffers **144a**, ..., **144n** and **148a**, ..., **148n** within each of the macro-function logic blocks. The output of the subtree **140** provides the clock timing signal to

the register **105** and the output of the subtree **145** provides the clock timing signal to the register **110**.

[0008] The clock skew for the clock distribution network is determined by the load that results from the number of buffers of a following layer being driven by an output of a buffer and by the physical wiring segments required to connect the output of the buffer to the input of the buffers of the following layer. It is not possible to either totally balance the number of buffers or the amount of wiring segment used in creating the clock distribution. Additionally, the structure of the two subtrees **140** and **145** may differ in the number of layers of buffers. Thus, the arrival times of the timing clock signals at the registers **105** and **110** may differ. These differences create the differences in arrival times of the clock timing signal or clock skew. In the present hierarchical design methods, the portion of the clock distribution system, within the macro-function logic blocks, are designed initially when the macro-function logic blocks are designed. Normally, the physical sizes or the macro-function logic blocks permit the structure of the clock distribution system to be well balanced to minimize the clock skew within the macro-function logic blocks. When the global interconnection of the clock distribution system are implemented, the distances between the macro-function logic blocks vary significantly. The clock skew at the global level can thus differ at the global or top level significantly more than within the macro-function logic blocks.

[0009] "Clock Generation and Distribution for the First IA-64 Microprocessor,"  
Tam et al. IEEE Journal of Solid-State Circuits, pp. 1545 – 1552, Nov. 2000,  
Volume: 35 Issue: 11, ISSN: 0018-9200 describes clock distribution with an  
active distributed deskewing technique. The technique is capable of  
5 compensating skews caused by within-die process variations that are becoming  
a significant factor of the clock design. A multilevel skew budget and local clock  
timing methodology are used to enable a high-performance design by providing  
support for intentional clock skew injection and time borrowing. A test access  
port interface is provided to the deskew architecture with the incorporation of the  
10 on-die-clock-shrink for post-silicon timing debug.

[0010] "Performance Optimization of VLSI Interconnect Layout," Cong et al. The  
Journal of VLSI Integration, Vol. 21, Nos. 1&2, November 1996, pp. 1-94  
presents a comprehensive survey of existing techniques for interconnect  
optimization during the VLSI physical design process, with emphasis on recent  
15 studies on interconnect design and optimization for high-performance VLSI circuit  
design under the deep submicron fabrication technologies.

[0011] "An Algorithm for Zero-Skew Clock Tree Routing with Buffer Insertion,"  
Chen et al. Proceeding - European Design and Test Conf., pages 652-- 657,  
1996 presents multi-stage zero skew clock tree construction for minimizing clock  
20 phase delay and wire-length. Chen et al. simultaneously performs clock tree  
routing and buffer insertion. A clustering-based algorithm, which uses shortest  
delay as the cost function, is described.

[0012] "Physical Design CAD in Deep Sub-micron Era," Mitsuhashi et al.,  
Proceedings of the European Design Automation Conference with EURO-  
VHDL'96, 1996, Geneva, Switzerland, IEEE Computer Society Press, Los  
Alamitos, CA, pp. 350 – 355, ISBN:0-8186-7573-X describes timing optimization  
and power minimization methods using the concept are discussed in detail.

[0013] "Wire segmenting for improved buffer insertion," Alpert et al., Proceedings  
of the 34th Annual ACM/IEEE Design Automation Conference, 1997, ACM  
Press, New York, NY, USA, pp. 588 - 593 ISBN:0-89791-920-3 presents buffer  
insertion, which seeks to place buffers on the wires of a signal net to minimize  
delay. Alpert et al. studies the problem of finding the correct number of segments  
for each wire in the routing tree. Too few segments yields sub-par solutions, but  
too many segments can lead to excessive run times and memory loads.

[0014] "Repeater Block Planning under Simultaneous Delay and Transition Time  
Constraints," Sarkar et al. Proceedings 2001 European Design, Automation and  
Test Conference, March 2001, pp. 540-544 describes a solution to the problem  
of repeater block planning under both delay and signal transition time constraints  
for a given floor plan.

[0015] U. S. Patent 6,311,314 (McBride) describes a system and method for  
evaluating the loading of a clock driver. The method evaluates each node within  
a net list file to determine: (1) whether that node is an output node for a clock  
driver; and (2) for clock driver nodes, whether that node is within loading  
specification for the particular clock driver circuit.

[0016] U. S. Patent 6,053,950 (Shinagawa) teaches a layout method for a clock tree in a clock signal distribution circuit. In the layout of the clock tree, a standard clock tree is prepared having a route buffer, a plurality of intermediate stage buffer cells and a plurality of last stage buffer cells connected in a hierarchical configuration. All of the clock lines have an equal length. If there is no set of flip-flops in a target integrated circuit corresponding to a set of last stage buffer cells, the set of last stage buffer cells are removed as a whole provided there is not other last stage buffer cells connected to a flip-flop.

[0017] U. S. Patent 6,020,774 (Chiu, et al.) demonstrates a gated clock tree synthesis (CTS) method for the purpose of synthesizing a gate array logic circuit to allow optimal topological arrangement of the gate array on the logic circuit.

[0018] U. S. Patent 5,864,487 (Merryman, et al.) illustrates a method and apparatus for identifying gated clocks within a circuit design using a standard optimization tool. The gated clock signals may be identified by identifying which of the number of raw clock signals is coupled, through combinational logic, to a selected one of the number of state devices. This results in an identified raw clock signal. A number of enable signals coupled through combinational logic to the selected one of the number of state devices is identified and results in an identified enable signal. The gated clock signals are then uniquely determined by the particular combination of the identified raw clock signal and the identified enable signal.

[0019] U. S. Patent 5,686,845 (Erdal, et al.) describes a hierarchical clock distribution system and method. The method of producing a hierarchical clock distribution system for the circuit includes determining clock skews between the clock driver and the sub-blocks respectively. Delay buffers are selected from a predetermined set of delay buffers having the same physical size and different delays, with the delay buffers being selected to provide equal clock skews between the clock driver and the distribution systems respectively. Each delay buffer includes a delay line, and a number of loading elements that are connected to the delay line, with the number of loading elements being selected to provide the required clock delay for the respective sub-block.

### Summary of the Invention

[0020] An object of this invention is to provide a method and apparatus for synthesizing a clock distribution system within an integrated circuit.

[0021] Another object of this invention is to provide a method and apparatus for compensating for clock skew within a global or top level clock distribution network.

[0022] To accomplish at least one of these objects and other objects, a method for synthesizing a clock distribution circuit within an integrated circuit device composed of a plurality of functional circuits begins with allocating at least one delaying circuit within each of the functional circuits. An intra-functional clock distribution network is fabricated within each of the functional circuits. Once the



intra-functional clock distribution network is fabricated, an inter-functional clock distribution network is constructed between each of the functional circuits.

[0023] The method continues by determining a clock skew for the inter-functional clock distribution network. The clock skew is then compensated by inserting the delaying circuit at a terminal of the inter-function clock distribution network where each of the functional circuits is connected to the inter-functional clock distribution network. The compensation for the inter-function clock skew is accomplished by determining a clock skew factor for one selected functional circuit connected to one selected terminal of the inter-functional clock distribution network. The delaying circuit is then adjusted within the one selected functional circuit to cancel out the clock skew factor.

[0024] The delaying circuit includes a plurality of delaying buffer circuits, each delaying buffer circuit having a first increment of delay. The delaying circuit also includes a plurality of interconnecting wiring segments placed between each of the plurality of delaying buffer circuits. Each of the interconnecting wiring segments has a second increment of delay. The adjustment of the delaying circuit is accomplished by connecting a first quantity of the delaying buffer circuits with a second quantity of the plurality of interconnecting wiring segments such that a sum of the first increment of delay of the first quantity of the delaying buffer circuits and the second quantity of delay of the interconnecting wiring segments is equal to the clock skew factor.

## Brief Description of the Drawings

[0025] Fig. 1 is a schematic diagram of a clock distribution system of an integrated circuit of the prior art.

[0026] Fig. 2a is a schematic diagram of a clock distribution system of an integrated circuit of this invention.

[0027] Fig. 2b is a schematic diagram a delaying circuit of the clock distribution system of an integrated circuit of this invention.

[0028] Fig. 2c is a schematic diagram illustrating an implementation of the delaying circuit of the clock distribution system of an integrated circuit of this invention.

[0029] Fig. 3 is a process diagram for the method for design of a clock distribution system within an integrated circuit of this invention.

## Detailed Description of the Invention

[0030] In an integrated circuit of this invention, the clock distribution circuit has a network of inter-functional buffer circuits connected to distribute a clock timing signal from a clock generator to each macro-function circuit of the integrated circuit device. Within each macro-function circuit, a network of intra-functional buffer circuits is connected to distribute the clock timing signal to the register circuits of each synchronous functional circuit. An adjustable delay block is placed at the boundary of each of the macro-function circuits. During the

physical design layout of the integrated circuit device, the intra-functional clock distribution network is designed. Once the global functions have been arranged on the semiconductor substrate and the intra-functional clock distribution network designed, the inter-functional clock distribution network is constructed. The differences of the delays for branch of the inter-functional distribution network is calculated to determine the clock skew for each of the branches. The adjustable delay blocks are then modified to account for the skew of each of the branches of the inter-functional or as commonly termed the top level clock distribution network.

[0031] For a more detailed discussion of the structure of a clock distribution system for an integrated circuit of this invention, refer now to Fig. 2a. The primitive logic circuits are configured to form a combinational logic function **215**. The registers **210** and **220** provide the memory elements for the sequential logic functions **205a**, ..., **205z**. The sequential logic functions **205a**, ..., **205z** are partitioned and organized to form the macro-function logic blocks **200a**, ..., **200n**. The macro-function logic blocks **200a**, ..., **200n** are arranged and placed physically on the semiconductor substrate.

[0032] A clock generator **225** provides the clock timing signal used to provide the synchronization of the data being transferred to and transferred from the registers **210** and **220**. The clock timing signal is transferred through a clock distribution system or clock tree from the clock generator **225** to the registers **210** and **220**. The clock distribution system or clock tree is a series of buffer circuits

placed in an ever widening network. Each buffer is generally a driver circuit constructed to provide an increment of delay to the clock timing signal and sufficient drive for the number of buffers in the next layer of buffers.

[0033] In the example of the clock distribution system, as shown, the clock timing  
5 signal is received from the clock signal generator **225** by the buffer **230**. The  
buffer **230** forms a first layer of the clock distribution system or clock tree. The  
output of the buffer **230** is connected to the second layer of buffers **232a**, ...,  
**232n**. Each of the buffers of the second layer of buffers **232a**, ..., **232n** is in turn  
connected to a group of buffers of the third layer of buffers **234a**, ..., **234z**. The  
10 first, second, and third layers of buffers form the global or top level of the clock  
distribution system and provide the inter-functional connections to distribute the  
clock timing signal to the macro-function logic blocks **200a**, ..., **200n**.

[0034] At the boundaries of the macro-function logic blocks **200a**, ..., **200n**, an  
area of delay cells are allocated to for a delay circuit block **250**. The delay circuit  
15 block **250** is placed at the interface of the macro-function logic blocks **200a**, ...,  
**200n** at the terminal **255** of the connections from the global clock distribution  
system. The outputs **257a**, ..., **257n** of the delay circuit block are selectively  
connected to the input terminal **260** of the intra-functional clock distribution  
system of the macro-function logic blocks **200a**, ..., **200n**. The selection of the  
20 outputs **257a**, ..., **257n** of the delay blocks **250** is determined by the clock skew  
from the connections of the inter-functional clock distribution system.

[0035] The intra-functional clock distribution system further distributes clock timing signal within the macro-function logic blocks **200a**, ..., **200n**. In the example as shown the output of the delay block **250** is connected to a group of buffers **238a**, ..., **238n** within each of the macro-function logic blocks **200a**, ..., **200n**. The output of each of the buffers **238a**, ..., **238n** is connected to a group of buffers **240** within each of the sequential logic function, which is connected to the buffers **242a**, ..., **242n**. The buffers **242a**, ..., **242n** are the final driving buffers that deliver the clock timing signal to the registers **210** and **220**.

[0036] As described above, the clock skew for the clock distribution network is determined by the load that results from the number of buffers of a following layer being driven by an output of a buffer and by the physical wiring segments required to connect the output of the buffer to the input of the buffers of the following layer. It is not possible to either totally balance the number of buffers or the amount of wiring segments used in creating the clock distribution. These differences create the differences in arrival times of the clock timing signal or clock skew. Once the intra-functional clock distribution system and the global or top level distribution system are configured, the clock skew for each is determined. The delay block **250** is then adjusted to compensate for the clock skew of the inter-functional clock distribution system. The output terminal **257a**, ..., **257n** is selected to provide the compensating delay for the clock skew.

[0037] Refer now to Fig. 2b for a discussion of an example of a structure of the delay block **250**. The terminal **255** of the inter-functional clock distribution

system is connected to the input buffer **270** of the delay block **250**. The delay buffers **272a**, ..., **272z** are designed to provide specific delay increments and maybe modified during design if other delay increments are desired. The delay buffers **272a**, ..., **272z** are serially connected output to input to form a delay chain. The output of each of the delay buffers **272a**, ..., **272z** are connected for distribution of the delayed clock timing signal to the output terminals **257a**, ..., **257n**. The adjustment of the delay block **250** entails the selection of the delay buffers **272a**, ..., **272z** to choose the appropriate delay increments for the delay buffers **272a**, ..., **272z** and then the choosing of the number of delay buffers **272a**, ..., **272z** (which terminal outputs **257a**, ..., **257n** to select) to provide the desired clock skew adjustment. Further, the compensation delay is modified by placing additional wiring segments between the delay buffers **272a**, ..., **272z** to more finely modify the compensating delay. Those delay buffers **272a**, ..., **272z** not selected for inclusion in the serially connected buffers to provide the compensation delay to reduce or eliminate the clock skew have their inputs connected to a substrate biasing voltage source ( $V_{ss}$ ) **274**.

[0038] Refer now to Fig. 2c for a configuration of the clock delay block **250**. The delays of the delay buffers **272a**, ..., **272z** designed to be set at incremental delay times  $\delta_1$ ,  $\delta_2$ ,  $\delta_3$ , and  $\delta_4$ . If the clock skew between two clock timing signals is determined to sum of the delays  $\delta_1$ ,  $\delta_2$ , and  $\delta_4$ , then the delay buffers **272a**, **272b**, and **272d** are serially connected together. The output **257x** of the delay buffer **272d** is connected to the input terminal **260** of the intrafunctional

clock buffers **238a**, ..., **238n**. The remaining delay buffers **272c**, **272** , ..., **272z** not connected have their inputs connected to the substrate biasing voltage source ( $V_{ss}$ ) **274**.

[0039] The method for the creation of the clock distribution system within the design procedure of an integrated circuit that is being placed on a semiconductor substrate is shown in Fig. 3. The delay block **250** of Fig. 2a of each of the macro-function logic blocks **200a**, ..., **200n** are allocated and placed (block **300**) within the macro-function logic blocks **200a**, ..., **200n**. The intra-functional clock distribution circuit for each of the macro-function logic blocks **200a**, ..., **200n** is then synthesized (block **305**). After the macro-function logic blocks **200a**, ..., **200n** are placed in their allocated locations on the substrate, the inter-functional global clock distribution circuit is synthesized (block **310**) to provide a distribution path for the clock timing signal to each of the macro-function logic blocks **200a**, ..., **200n**. The clock timing skew of inter-functional global clock distribution circuit is then determined (block **315**). The delay blocks are then modified (block **320**) as described in Fig. 2b and inserted (block **325**) between the inter-functional global clock distribution circuit and the intra-functional clock distribution circuit to compensate for and thus eliminate clock skew for each branch of the inter-function global clock distribution circuit. The standard EDA system tools are then exercised to complete the placement, wiring, and checking of the design to complete the integrated circuit for manufacturing.

[0040] While this invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made without departing from the spirit and scope of the invention.

5 [0041] The invention claimed is: